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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF FACTORS AFFECTING PILOTS' ABILITY TO UTILIZE A RADARSCOPE DISPLAY OF STEERING INFORMATION

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FLIGHT INVESTIGATION OF FACTORS AFFECTING PILOTS' ABILITY TO UTILIZE A RADARSCOPE DISPLAY OF STEERING INFORMATION

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SUMMARY

Results are presented of a flight investigation of a radar fire-control system installed in a fighter airplane. Some of the factors of the radarscope display are evaluated from consideration of their effects on the ability of the pilot to maintain low aim wander when utilizing a radarscope type of presentation of target position. These factors included "noise" (extraneous motions) of the steering dot, lack of target-attitude information, and sensitivity and linearity of the display. The results are presented for limited flight conditions.

The results of the noise investigation showed that, as the noise level increased, the tracking performance deteriorated rapidly. The results also indicated that small amounts of noise may not seriously affect the tracking performance. These results were not obtained by any systematic variation of the noise level, but rather by a noise variation assumed to be due to the regenerative effects within the pilot-airplane-radar combination.

The results of the tests of a nonlinear display (sensitivity reduced at large displacements) indicated that this display did not give the pilot enough information to allow him to track satisfactorily in all situations. Furthermore it was the pilot's opinion that increasing the angular range in which the display was linear by reducing the sensitivity of the display through the center would not be advisable from the standpoint of maintaining small aim wander in steady tracking.

The results of the tests to determine the effects of lack of target outline showed that, in general, the aim wander without target outline were only one-third to one-half greater than those of visual tracking and should not be large enough to affect seriously hit probability.

[redacted]

INTRODUCTION

With the advent of airborne radar fire-control systems, greater flexibility has been afforded interceptor operations, particularly from the all-weather standpoint. However, these radar systems, as compared to the previous optical systems, have produced new problems and variables which must be studied in order to obtain a high level of efficiency.

The Flight Research Division of the Langley Laboratory has conducted flight tests using an early type of Navy radar fire-control system in an attempt to obtain some of this basic information. The primary purpose of these tests was to evaluate some of the factors which might affect the ability of the pilot to maintain low aim wander when utilizing a radarscope presentation of target information while tracking.

Results of this investigation are presented herein. Specifically, the paper covers results related to the effects of the presence of steering-dot "noise" and of lack of target-attitude information (target outline). In addition, a discussion is presented of some qualitative results as to the effects of the sensitivity and linearity of the radarscope display on the aim wander.

BASIC DIFFERENCES BETWEEN OPTICAL AND RADAR FIRE-CONTROL SYSTEMS

Although experimental information is available on the ability of pilots to track targets by using optical fire-control systems (refs. 1 and 2) this information cannot be extrapolated for application to radar systems because of the differences between the optical and radar systems. A difference which is immediately apparent relates to the inability of the radar system to display to the pilot the outline of the target. Since the predicted position of the target is presented as only a dot on the radarscope, the pilot is required to provide considerable interpretation of the radarscope display over that required for optical display in order to establish the nature of the tactical situation. The anticipation provided the pilot through knowledge of target rolling rate and bank attitude in optical display is not available in the radar display.

A second and perhaps more important difference is concerned with the effects of the inherent noise of the radar display on the aim wander. Whereas the optical system defines the line of sight exactly to the pilot, the radar system is affected by noise and is therefore unable to define exactly the target position. The noise comes principally from four sources: servo and electronic noises in the fire-control equipment, and angular and amplitude scintillation of the radar reflection from the target. Because the noise obscures the actual point of aim, there is a deterioration in the ability of the pilot to track.

A third difference between optical and radar systems is the fact that the direct indication of the magnitude of the aiming errors afforded by the optical systems may be modified when the same errors are presented as steering information on a radarscope. Three important factors affecting the relationship between the actual aiming errors and amount of deflection are the average sensitivity, the static linearity of the display, and the shaping as a function of frequency afforded by electronic networks.

A fourth significant difference concerns the manner in which the lead angle is computed in the two types of systems. In the optical system the space rate of airplane motion is used in the lead-angle computation and the tracking line (sight pipper) is deflected behind the gun line in order to create lead (called a disturbed reticle system). In most radar systems the antenna (tracking line) is kept, insofar as possible, pointed at the target and the space rate of the antenna is used in computing the lead angle (amount of displacement of the steering dot from a point corresponding to the true target position). Systems using this method of computing lead angle are often termed director systems. As a result of these differences, pilot tracking with the optical system is usually more affected by "own-ship" motion.

The object of the investigation reported herein is to explore the manner in which the first three of the aforementioned basic differences listed affected the tracking performance of the airplane-pilot combination. Some effects related to the fourth item, that involving the computation of lead angle, have been reported in reference 3. In the present tests the lead angle inputs of both sighting systems were eliminated in order better to isolate the other effects.

APPARATUS

The flight tests were conducted by using a two-place Navy night-fighter airplane. A photograph of the airplane is shown in figure 1. The airplane was equipped with an early type of radar fire-control system. This equipment incorporates both automatic search and tracking modes. The search component of the fire-control system was used to detect the target and to vector the pilot to within the lock-on range of the automatic tracking component. Once the automatic tracking component locked on the target, the pilot was supplied with steering information on a radarscope which provided an indication of the magnitude and direction of the error by the displacement of a dot from the center of the scope. A photograph of the radarscope is shown in figure 2(a). An indication of true horizon was given the pilot by a line (more correctly a flattened loop) on the scope. The bank-angle and pitch-angle indications were considered by the pilot to be adequate up to the maximum angles used in these flights. The radarscope was 3 inches in diameter and was mounted slightly below and to the right of the normal line of sight of the pilot. The steering-dot calibration was adjusted to be approximately 3° per inch through the center of the scope. At this sensitivity and with the existing distance between the radarscope and the pilot's eyes, the dot displacement subtended a visual angle about equal to the true tracking error.

The airplane was also equipped with an optical sight. The sight was boresighted parallel to the armament datum line, which was also the boresight line for the radar fire-control system.

The sight was used in conventional manner during visual day tracking runs and also at night. For these night flights a bright light was attached to the tail of the target and at the range used in the tests only the special light was visible. These runs were made to isolate effects on tracking attributable solely to lack of target attitude reference. The night presentation of target-position information, a white dot on an otherwise black background, was similar to the presentation of a radarscope. (See fig. 2(b).) There were, however, none of the other factors such as sensitivity, nonlinearity, or noise which normally cause the radarscope presentation to differ from a visual display.

In order to evaluate the tracking performance, motion pictures of the target were taken through a fixed gunsight while a second camera photographed the pilot's radarscope. The relationship between the true target position, the aiming point, and the radar-indicated target position is shown in figure 3. The lead angle inputs to both the radar fire-control system and the optical sight were eliminated to reduce the number of test variables. The main effect of elimination of these inputs was to reduce the noise level of the radarscope display. Elimination of the lead-angle computation simplified the analysis by affording a direct comparison between the recorded radar and optical tracking data.

The steering-dot display on the radarscope was calibrated by an analysis of all the flight data and this calibration is shown in figure 4. The curves are the faired averages of the true control-line errors as recorded by the gunsight camera for given scope displacements. Also shown on the calibration figures are the root-mean-square values of the true control-line errors about the calibration curve. As can be seen from figure 4, this root-mean-square variation in control-line position was about 5 mils in both yaw and pitch. Because of a coupling between the airplane motions and the radar, however, the root-mean-square values obtained in a given test run were found to depend on the pilot's aim wander (and vice-versa). Another pertinent feature of the radarscope display illustrated by the calibrations was the nonlinear sensitivity of the target dot. The sensitivity reduced rapidly as the displacement from the center increased, the sensitivity being roughly one-sixth the maximum at

1/2 inch from the center. Because of this nonlinearity, full-scale excursions $\left(1\frac{3}{8}\ \text{in.}\right)$ of the target dot corresponded to a very large error (greater than 25°).

The airplane was also instrumented with standard NACA instruments for recording altitude, airspeed, control-surface positions, stick and rudder forces, three components of angular rate and three components of airplane acceleration. The target airplane was similarly instrumented and, in addition, was provided with equipment to synchronize the film records of the two airplanes.

TESTS

The investigation covered three types of tracking: tracking by means of the steering information from the automatic tracking radar, tracking during the day by use of the fixed optical sight, and tracking at night by means of the fixed optical sight with the special light on the tail of target. For purposes of the present discussion, these tracking types are referred to as radar, day, and night, respectively.

The tests consisted of a series of runs in which the target airplane performed certain steady maneuvers with various degrees of intensity. These maneuvers were generally begun from a straight and level tail chase and consisted of level turns, pull-ups, push-downs, and longitudinal oscillations. In some cases, two maneuvers were combined in a single run, such as a turn and reversal. The sequence of the maneuvers was random and the tracking pilot had no prior knowledge of the maneuver to be perfomed during a run. In order that range and range rate would not be a variable factor in these tests, the pilot established a zero closure rate before each run at a range of approximately 1,000 yards. If the range was reduced to less than 600 yards, the run was discontinued. The pilot was instructed to track the target as accurately as possible throughout the entire run. An individual run lasted from 20 to 60 seconds.

The flight tests were performed at an altitude of 25,000 feet and at a true airspeed of 295 knots. Under these flight conditions the armament datum line, and consequently the boresight line, was elevated approximately 2° from the flight path. The yaw-damper channel of the autopilot of the airplane was used in all runs.

DATA REDUCTION

The motion pictures of the target taken through the gunsight and those of the radarscope were analyzed, frame by frame, to determine the aiming error, that is, the displacement of the target from the control line. The control line was defined by the mean position of the optical line of sight during a tail chase of a nonmaneuvering target and was obtained for each flight. The time history of each run was broken down into three parts: tail chase, transition, and steady accelerated flight. Figure 5 is a typical time history. The initial part of these runs, the tail chase, was assumed to end and transition to begin when the error became greater than 1.4 times the root-mean-square of the aim wander of a steady tail chase. The end of transition and beginning of steady accelerated flight was determined by visual inspection of the control-line-error time histories and was the point after which the aim wander was relatively steady or at least the error was regular. The steady accelerated part of the run lasted as long as the target maintained the maneuver and varied in length from 5 to 40 seconds. The root-mean-square of the error of each of these major parts was found and was used to evaluate the various conditions of the test. In some runs the tracking airplane encountered the wake from the target airplane and was abruptly deflected up to 100 mils off the target. When these effects were obvious in the time histories, these parts of the run were deleted from the aim-wander calculations. In those runs in which a second maneuver was performed, the procedure described previously was repeated. If two or more similar runs existed, the results were averaged.

The effect of display noise on the tracking performance could not be determined directly as it was not feasible to produce an independent variation of the noise. The effects of noise were determined through the use of the procedures discussed in the following paragraphs.

In the radar tracking tests, a large variation of aim wander with target-maneuver severity was noted. From time histories of the radar-indicated error and the control-line error, it was observed that higher display noise levels existed whenever the aim wander was large. Since the night tracking tests showed only a relatively small increase in aim wander with maneuver severity, it is believed that the larger radar aim wander might be attributed primarily to the increased display noise. When the pilot tracks by using radar-steering information, apparently the normally minor effects of the aim wander due to maneuver severity indirectly produce larger effects due to a regenerative-coupling condition between the aim wander and the display noise. On the assumption that most of the increase in aim wander with increased maneuver severity could be attributed to an increase in display noise, an analysis was made by utilizing the data obtained to evaluate the effect of display noise upon radar tracking. In the analysis, noise was considered equal to the difference between the instantaneous values of the control-line error and the radar-indicated error. For this calculation the radar error was converted to mils by use of the calibration curves shown in figure 4. In order to determine the relative variation of true aim wander and display noise, the parts of the runs previously mentioned (tail chase, transition and steady accelerated flight) were grouped into three categories of aim wander. These categories were for values of root-mean-square errors of 5 to 10 mils, 10 to 15 mils, and 15 mils or more. The root-mean-square of the noise and of the aim wander were determined for each category and were used to evaluate the effects of the noise. All available runs were used irrespective of target maneuver.

RESULTS AND DISCUSSION

Before the data-obtaining phase of the test program was begun, a number of flights were made to acquaint the test pilot with the task of radar tracking. In addition to these flights, contacts were made with pilots of operational squadrons in order to obtain information concerning the problems of radar tracking and of the tracking techniques currently recommended. Use was made on one occasion of a ground simulator of the airplane and fire-control system in which radar tracking was practiced. These flights and discussions allowed the test pilot to reach a high degree of proficiency so that learning would not be a factor in the results.

As experience was gained in tracking with the radar and as preliminary tracking data were studied, it became apparent that the noise in display was a predominant factor affecting the tracking performance. As stated previously, noise is considered in this paper as the overall inaccuracy of the display in presenting true target position. Figure 6 shows the root-mean-square of the control-line error as a function of the root-mean-square of the noise. Also shown are points representing the average aim wander of all the night runs, irrespective of maneuver. These latter points indicate the magnitude of the tracking error for a scope-type display but without noise and with a sensitivity and linearity identical to that existing for optical tracking through a gunsight. These points are connected with the radar tracking test points by an intuitive fairing.

The figure shows that, with noise, the tracking performance as indicated by the root-mean-square of the control-line error increased rapidly with increasing noise level. The decrease in tracking performance with increasing noise from the no-noise point along the suggested fairing indicates that at low values of noise (below 2 to 3 mils) the noise on the display may not seriously affect the pilot's ability to track. As discussed previously, the data of this figure were not obtained by any systematic variation of the noise level. The variation was assumed to be due to the regenerative effects within the pilot-airplane-radar combination. The fact that the noise variation was thus obtained should not, however, affect the general conclusion obtained from figure 5. Nevertheless, the variation of aim wander with noise, especially in the low noise range, should be established in tests in which noise is the independent variable.

It is of interest to note that the radar had a noise level of about 3 mils when the regenerative effects were not present. This value was obtained from an extrapolation of the radar points of figure 6 and from data obtained from runs in which the pilot tracked visually while the radar was locked on. The fact that the noise is regenerative and that the tracking deteriorated with increasing noise shows that radar fire-control systems must be made as independent as possible of the airplane's (own-ship) motions.

The effects of nonlinear radarscope display on the tracking performance could be obtained in only qualitative manner from the recorded data of these tests. The effects are demonstrated by the time history shown in figure 7. This run was on a nonmaneuvering target and was started with an initial offset error in yaw of about 15°. The figure shows the radarscope indicated error in inches and the true error in mils. The angle of bank of the tracking airplane also is shown. Factors to be considered in analyzing this figure are that the dot on the scope was about 1/10 inch in diameter and that the pilot had no grid on the scope other than the cross hairs at the center. (See fig. 2(a).) Also to be considered is the fact that a finite time is required for the human to react to a stimulus. From figure 7 it can be seen that during the early part of the run, the small amount of dot motion gave the pilot little idea of how rapidly he was reducing the azimuth error. This was due to the low sensitivity of the radarscope in the high error range. When the rate of the dot motion became sufficiently high to give the pilot a cue to the rapid rate of error reduction, it was too late for him to prevent an overshoot. In fact, the pilot was unable to keep the dot in the high-sensitivity range of the radarscope. On the second attempt the pilot arbitrarily used a slightly lower rate of yaw-error reduction and was more careful in detecting small deflection changes in the low-sensitivity range of the scope. The pilot was still not able to prevent overshooting, but he was ultimately able to establish a steady tracking condition.

Obtaining the desired linearity of the display by use of the expedient of reducing the sensitivity through the center while maintaining the same total angular coverage is not considered advisable. It was the pilot's opinion that if this expedient were attempted, small errors would not be evident to the pilot and the quality of tracking in all maneuvers would deteriorate. This requirment that the sensitivity must be kept high was substantiated, to some extent, by a flight made by a service pilot in a similar service airplane with similar radar fire-control equipment. The radarscope in this service airplane had a reduced sensitivity through the center of 6° per inch and had similar nonlinear characteristics. (The test radarscope had 3° per inch through center.) Differences in the conditions of these tests preclude exact comparison; however, the statement can be made that the aim wander obtained with the low-sensitivity radarscope was about twice that obtained with the high-sensitivity radarscope. Other methods currently used to increase the angular range in which the display is linear, such as combined high and low sensitivity indicators, were not tested.

The results of the investigation of the effects of lack of target outline and also results of actual radar tracking are presented in figures 8 and 9. These figures show the resulting aim wander during turns and longitudinal maneuvers for day, night, and radar tracking. The abscissas of the figures are target bank angle and target incremental normal acceleration. These two quantities are used as a measure or indication of the severity of the maneuvers. The results are shown for the steady-tracking constant-acceleration parts of the maneuvers. The average record length was 28 seconds for the turns and 8 seconds for the longitudinal maneuvers.

Figure 8 shows the aim wanders for day and night tracking. As described previously, the investigation of the effects of lack of target outline was conducted without the use of the radar steering equipment and therefore is free of all effects of noise. The figure shows that, in general, the tracking without target outline resulted in aim wander one-third to one-half greater than day tracking, with the greater increases being in the longitudinal maneuvers.

The greatest increase in aim wander occurred in yaw tracking of longitudinal maneuvers. As might be anticipated in day tracking of longitudinal maneuvers, little variation of yaw aim wander with maneuver severity occurred. The yaw aim wander occurring in longitudinal maneuvers at night, however, increased with increasing maneuver severity. Even so, in this worst case, the maximum night aim wander was only about 6 mils. In view of the magnitudes of the other factors affecting the dispersions of air-to-air gunnery, this value of aim wander is not considered so large as to affect seriously hit probability.

Figure 9 shows a comparison between the results for the night flights and the radar steering flights for tail chase and for a series of turns. The results show that the radar aim wander was increased by a factor of 4 to 5 over those of night tracking and also that the aim wander increased sharply with maneuver severity. From the night flight data, it was seen that, under the conditions of a simulated radar presentation having no noise and a linear display, the maneuver severity had only minor effects on the aim wander. This result indicates that noise and nonlinearity are the primary cause of the increase in aim wander with the radar system.

The tracking during the transition into maneuvers showed the same general trends as the tracking during the steady-state portions of the maneuvers. There was a noticeable but not large increase in the night-tracking transition errors compared with the day-tracking errors. The radar-tracking transition phase usually showed a large increase in the magnitude of error and an appreciable increase in the length of the transition time over the values obtained with optical tracking. For all three types of tracking, the transition characteristics were inconsistent when runs involving a given target maneuver were repeated. It was not unusual, even for the radar tracking, for the transition in a particular run to consist of simply a gradual change from the steady tail-chase tracking to the steady maneuver tracking and then, when the same maneuver was repeated, for the transition to show a comparatively large error buildup similar to that shown in figure 5 that would settle into the steady maneuver tracking. Because of these wide variations in characteristics and the fact that only a limited number of runs were available, a quantitative analysis of the transition phase was not attempted.

CONCLUSIONS

Flight tests of a radar fire-control system installed in a Navy fighter airplane have been made to determine the effects of noise, nonlinearity, and sensitivity of the radarscope display on the tracking capabilities of the pilot. Flight tests were also made to determine the effects of lack of target outline on the tracking performance. The results are presented for limited flight conditions and indicate as follows:

1. The results of the noise investigation showed that as the display noise level increased, the tracking performance deteriorated rapidly. However, the results indicated that small amounts of noise may not seriously affect the tracking performance.

2. The results of the tests of a nonlinear display (sensitivity reduced at large displacements) indicated that this display did not give the pilot enough information to allow him to track satisfactorily in all situations. Furthermore the pilot's opinion was that an increase in the angular range in which the display was linear by reducing the sensitivity of the display through the center would not be advisable from the standpoint of maintaining small aim wander in steady tracking.

3. The results of the tests to determine the effects of lack of target outline showed that, in general, the aim wander without target outline were only one-third to one-half greater than that of visual tracking and should not be large enough to affect seriously the hit probability.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 1, 1956.

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3. Rathert, George A., Jr., Abramovitz, Marvin, and Gadeberg, Burnett L.: The Effects of Powered Controls and Fire-Control Systems on Tracking Accuracy. NACA RM A55D12A, 1955.

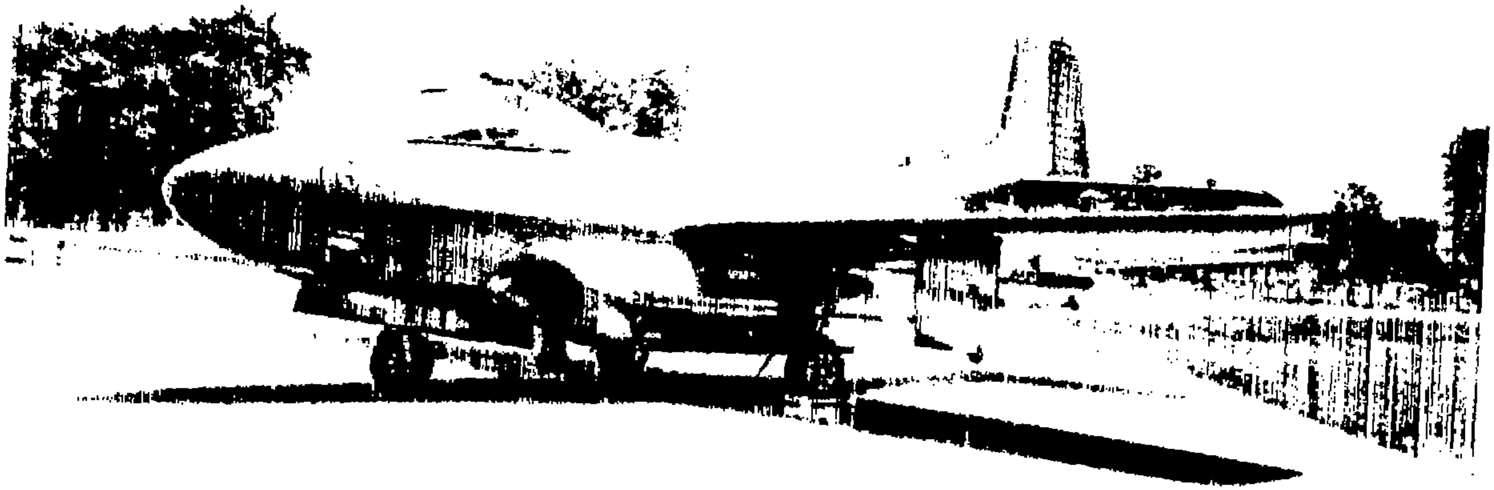

Figure 1.- Photograph of airplane.

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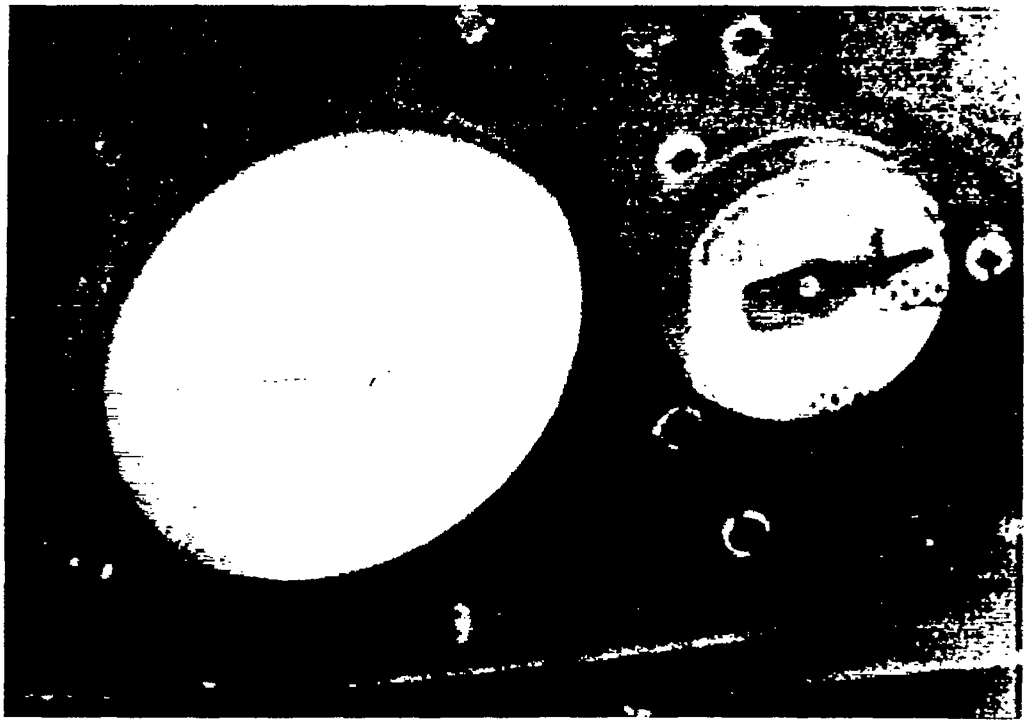
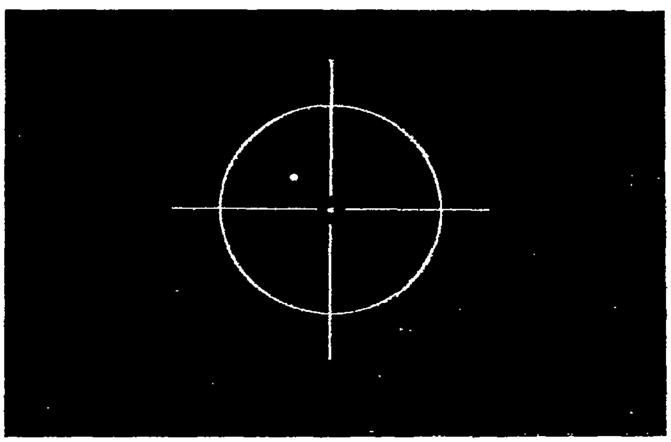


(a) Photograph of radarscope and range dial.



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(b) Appearance of optical sight at night, the light on the tail of the target airplane appearing in the upper left quadrant.

Figure 2.- Target displays used in the test airplane as they appear to the pilot.

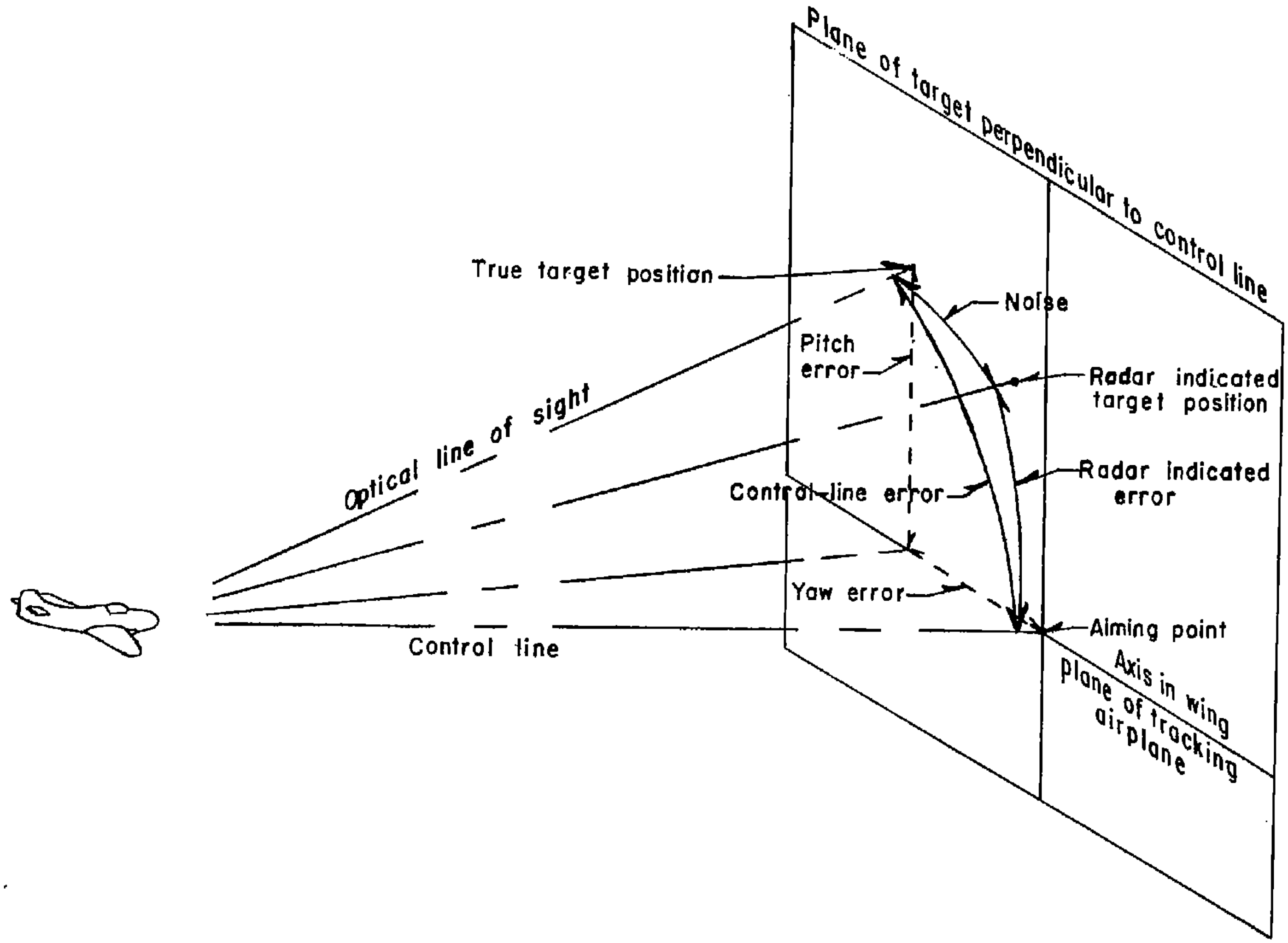
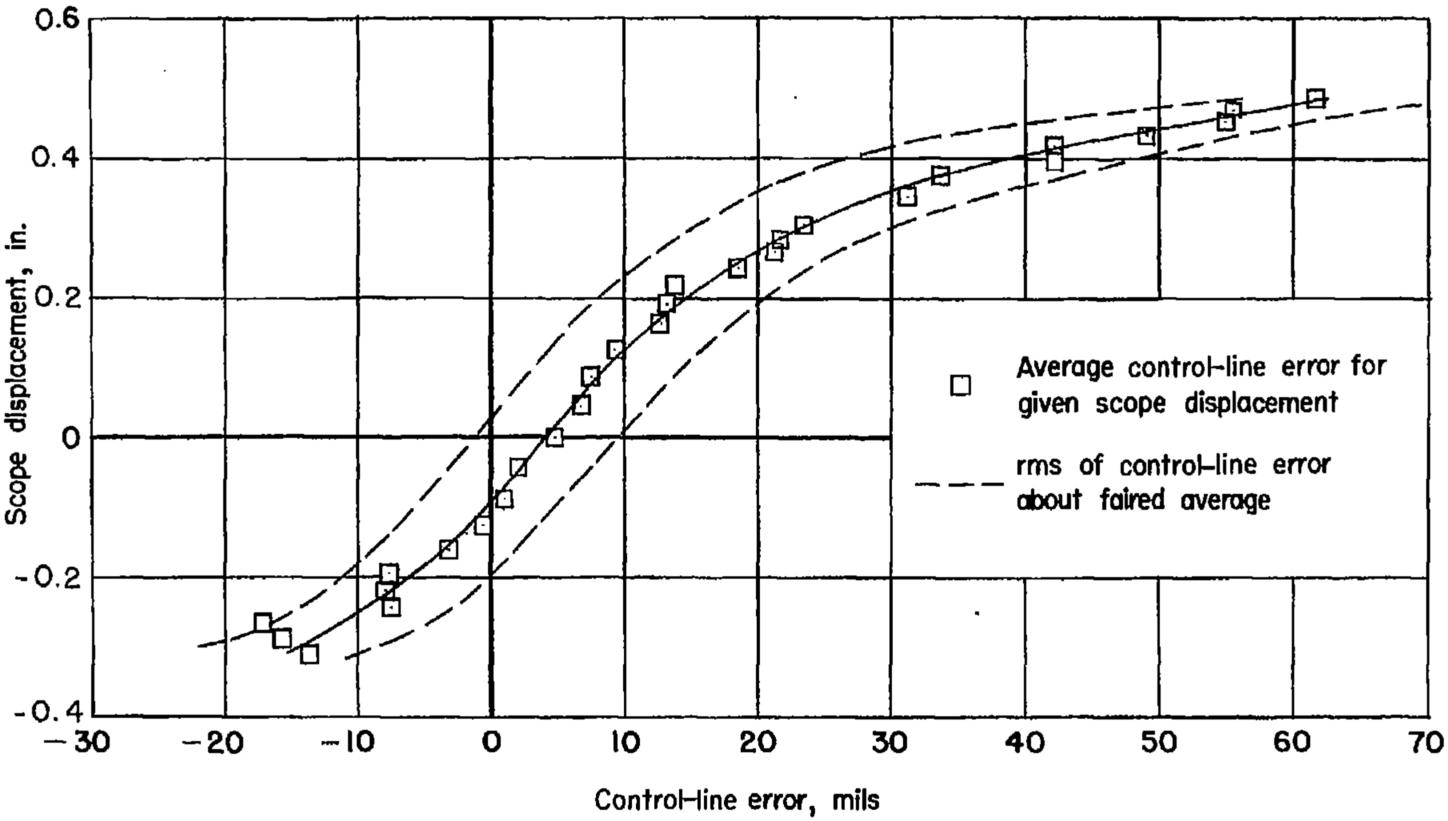
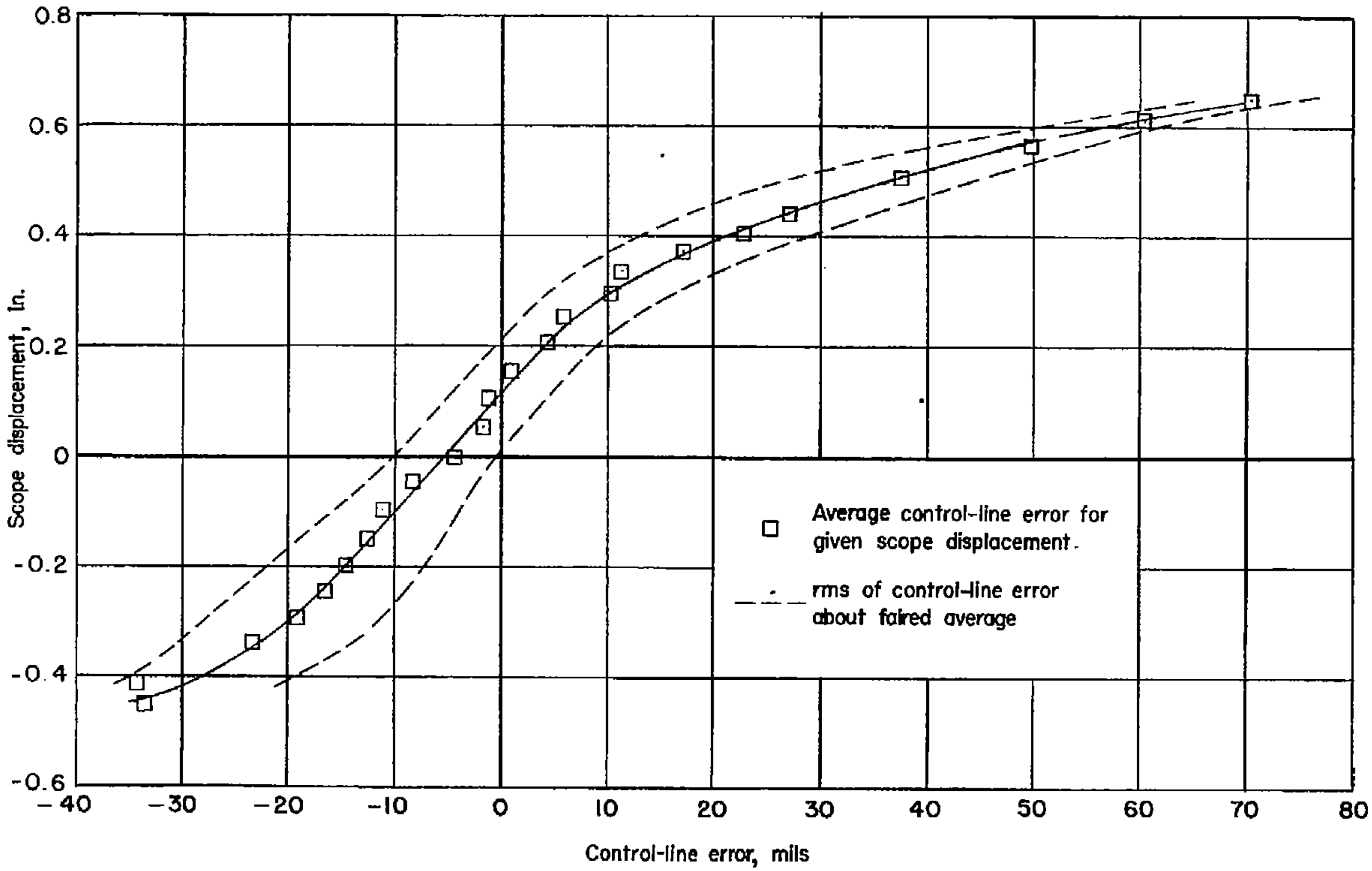


Figure 3.- Sketch showing relation of true target position, radar target position, and aiming point.



(a) Pitch.

Figure 4.- Calibration of radarscope showing displacement of dot on the scope as a function of the true error.



(b) Yaw.

Figure 4.- Concluded.

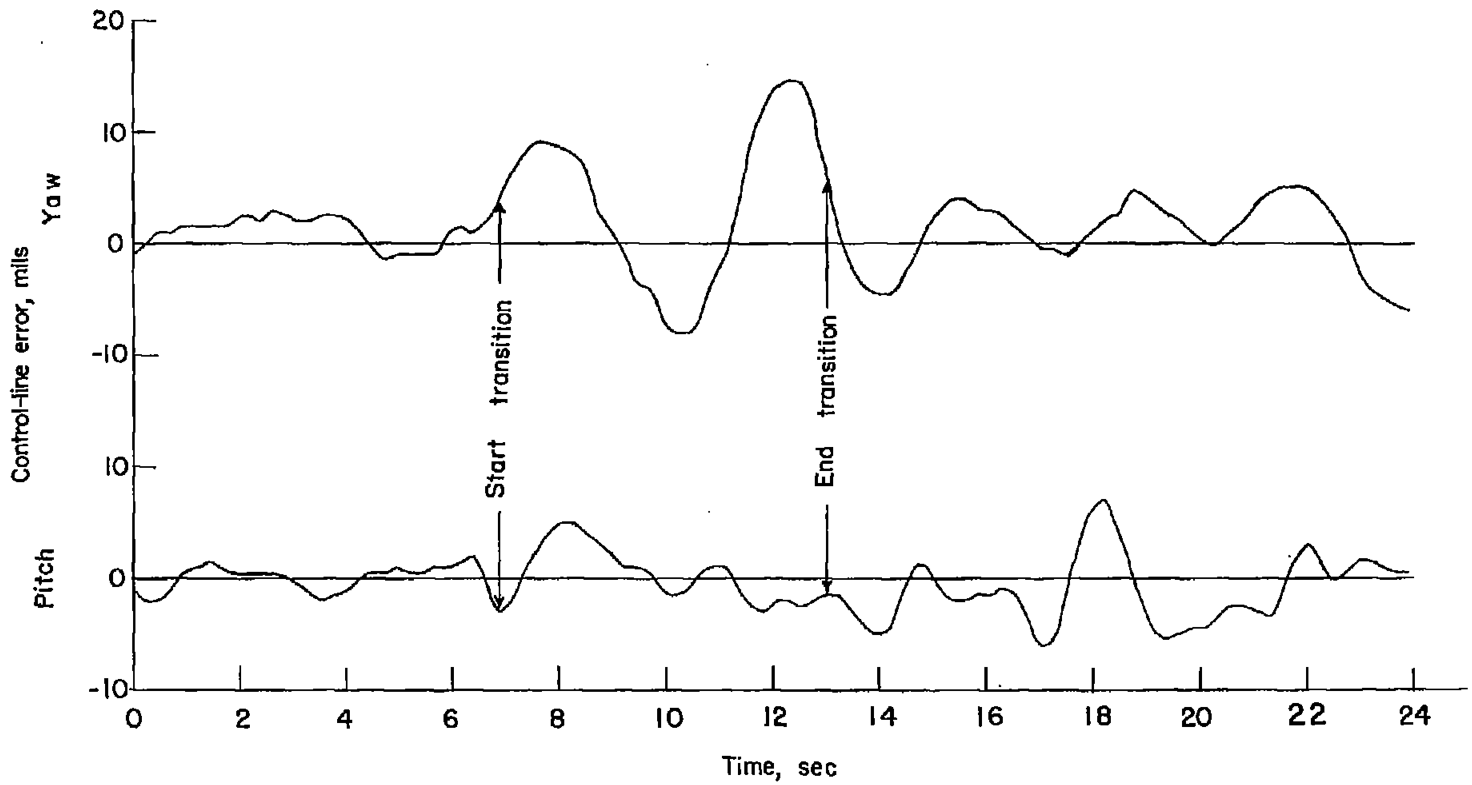


Figure 5.- Typical time history of the control-line error showing start and finish of transition.

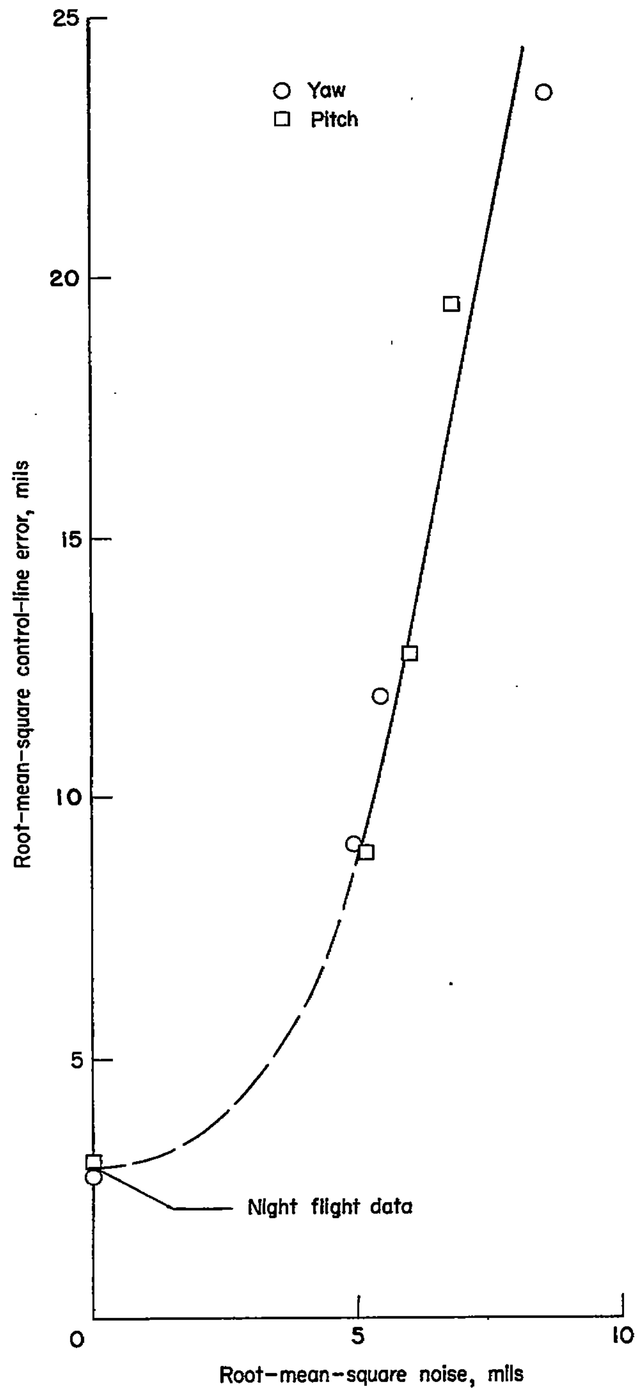


Figure 6.- Variation of tracking performance with the noise level of the target dot.

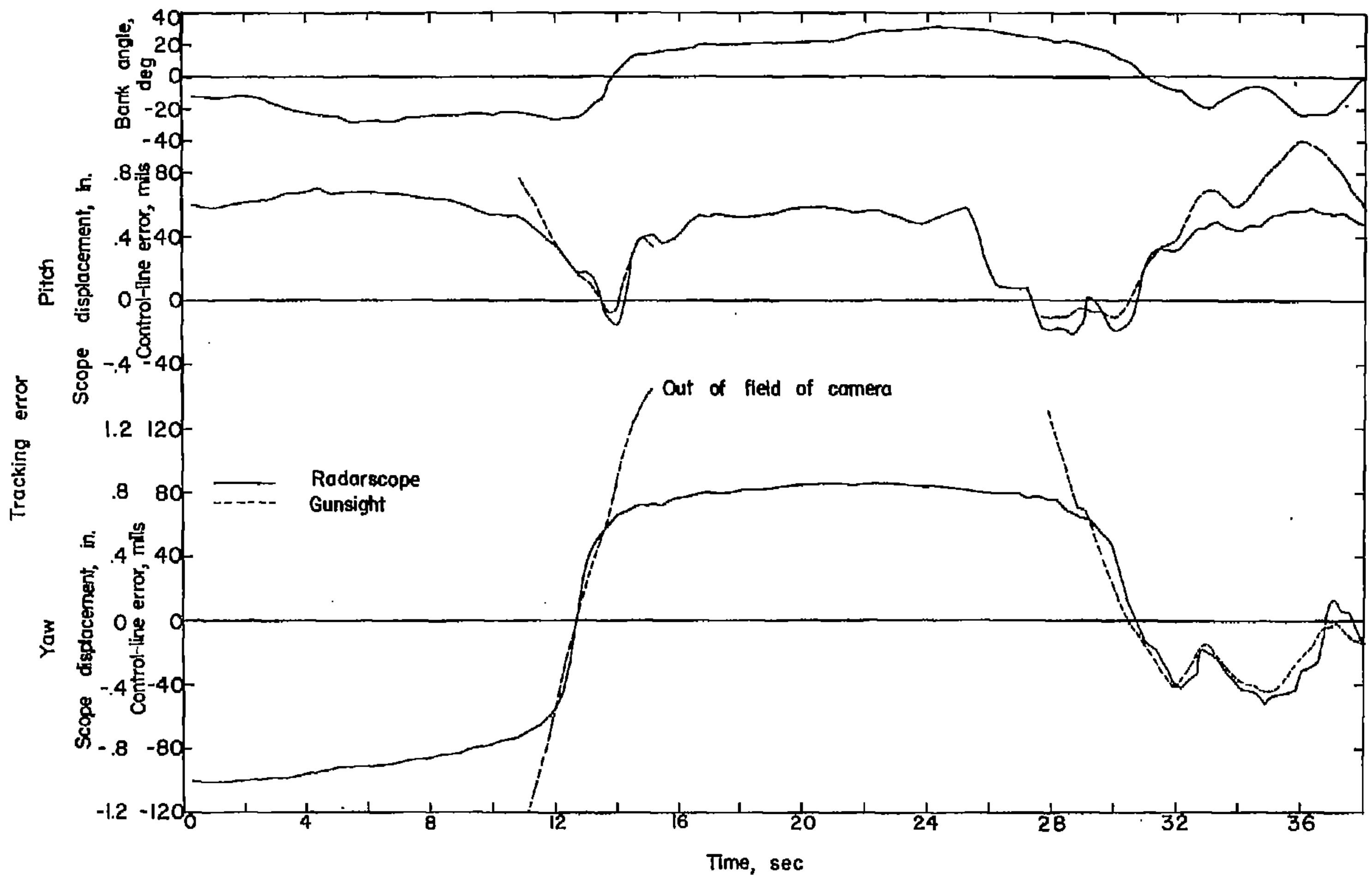
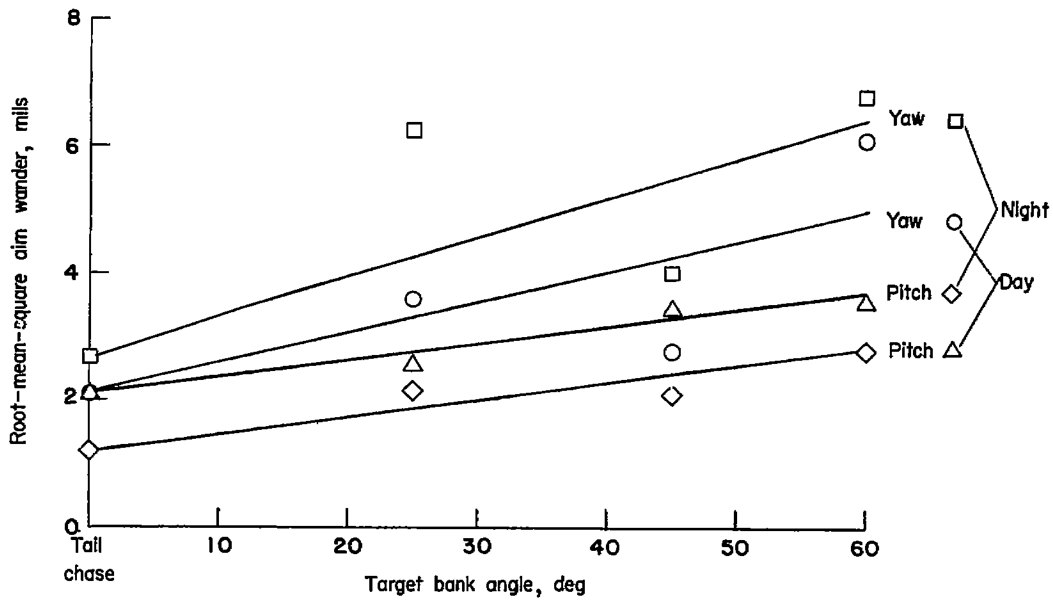
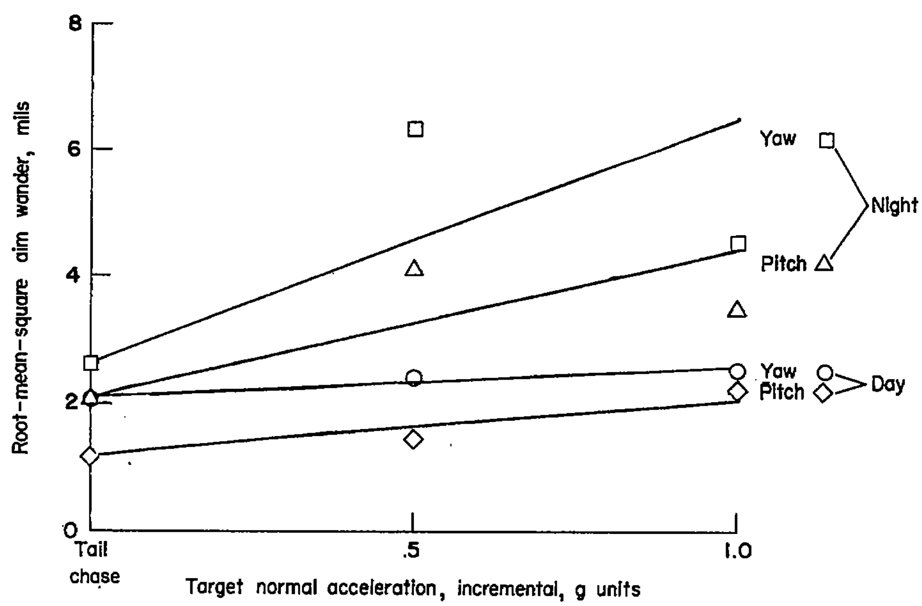


Figure 7.- Time history of a tracking run initiated from an offset in yaw of 15°.



(a) Steady turn maneuver.



(b) Steady longitudinal maneuver.

Figure 8.- Variation of aim wander with maneuver severity for day and night tracking.

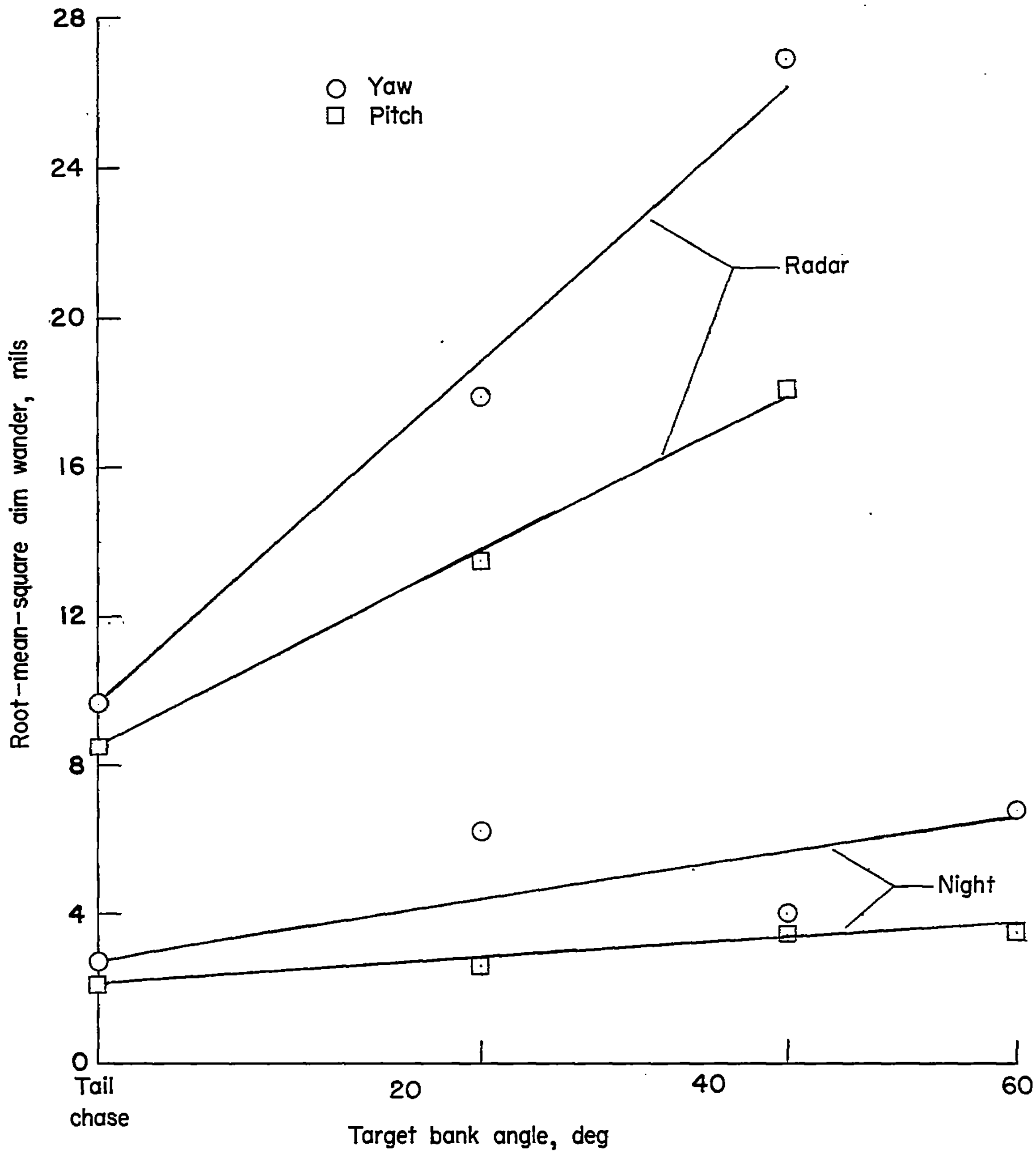


Figure 9.- Variation of aim wander in steady turn maneuvers for night and radar tracking.